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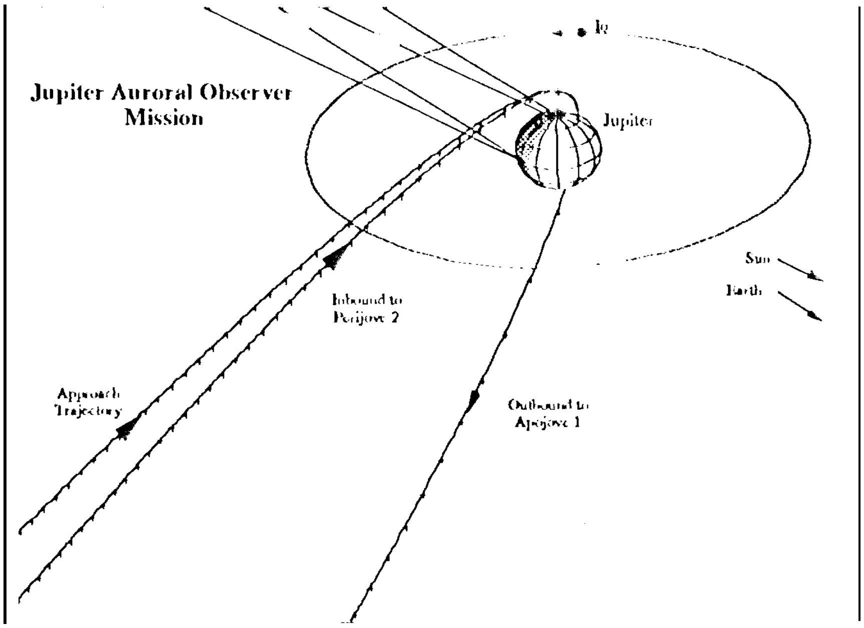

MEASURE-JUPITER: Low-Cost Missions to Explore Jupiter in the Post-Galileo Era

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ABSTRACT

MEASURE-Jupiter is a mission concept for the first wave of new missions to explore the giant planets in the post-Galileo era. This paper addresses the feasibility of low-cost, focused science missions to explore Jupiter based on the science information returned by the Galileo mission. Delivery mass performance for spacecraft in the range of 100 to 200 kg is analyzed for the Delta II low-cost launch vehicle. Judicious selection of advanced technology allows flyby and orbiter mission concepts powered by solar cells and trickle-charged secondary batteries. Two concepts, Io Skimmer and Jupiter Auroral Observer, are described as examples of MEASURE-Jupiter mission possibilities. Total life-cycle costs (i.e., including the cost of system development, launch vehicle, and mission operations and data acquisition) are estimated to lie in the range of $200 to $275 million.

INTRODUCTION

MEASURE-Jupiter is a new NASA Outer Planet Science Working Group-derived mission concept for the exploration of giant planets, with initial application at Jupiter. By flying sets of lightweight spacecraft with highly focused measurement objectives, it is designed to demonstrate that outer planet exploration is feasible in the era of small, low-cost missions. The MEASURE-Jupiter concept is characterized by: 1) intensive exploration of a giant planet system, 2) multiple small missions flown in focused waves using flight systems costing $100 to $200 million, and 3) missions launched every 2 to 3 years.

Why Jupiter? Jupiter is arguably the most complex planetary system in the Solar System with many scientifically intriguing bodies and phenomena to explore. The Galileo mission will intensify interest in the exploration of Jupiter, posing many questions for the MEASURE-Jupiter missions to address. Jupiter is also the easiest planet in the Outer Solar System to reach, making possible flight times of 2 years and total mission durations of 3 years or less.

Concept design studies conducted in collaboration with the NASA Outer Planet Science Working Group[1] have uncovered a number of scientifically rewarding, simple, low-cost mission options. These options have the additional attraction of being able to launch on 2-year trajectories to Jupiter with low-cost Delta II expendable launch vehicles. A partial list of mission concepts studied to date includes: Io Skimmer (very close flyby), Auroral Observer and Mini-Orbiters, Atmospheric Mini-Probes, and Galilean Satellite Penetrators. Two of these are described in some detail as examples in this paper: Io Skimmer and Jupiter Auroral Observer.

Key to the realization of the MEASURE-Jupiter concept is the judicious use of new low power consuming advanced technology and applicable systems from the Pluto Fast Flyby mission spacecraft design. In addition, because Jupiter is so much closer to the Sun than Pluto, elements of a hybrid solar array/battery power system make it possible to perform the identified missions without requiring Radioisotopic Thermoelectric Generators (RTGs). This relieves the mission design of the attendant programmatic complexities, costs, and constraints associated with the use of RTGs.

The following topics are covered in this paper:

- MEASURE-Jupiter as a set of small missions
- Delivery mass performance
- Example mission descriptions: 10 Skimmer and Jupiter Auroral Observer
- Technology requirements
- Jovian System environmental risks
- Cost estimates
- Conclusions

SMALL JUPITER MISSIONS

The MEASURE-Jupiter mission scope is specifically geared to small missions which have the following attributes:

- Focused science
- Delta II launch vehicle
- Fast trajectory to Jupiter (2 to 3 yrs) with encounters/playback times of 6 to 12 months
- No RTGs
- Common spacecraft subsystems and design elements, permitting a wave of spacecraft exploration
- Use of advanced spacecraft and instrument technology to achieve miniaturization, data quality, and cost control requirements

DELIVERY MASS PERFORMANCE

The launch vehicle of choice for MEASURE-Jupiter is the Delta II (7925) due to this vehicle's low cost. Figure 1 provides the performance capability of the Delta II (7925) alone, as well as with an additional upper stage, the Star 30BP, a relatively inexpensive solid rocket motor that will fit within the shroud of the Delta II.

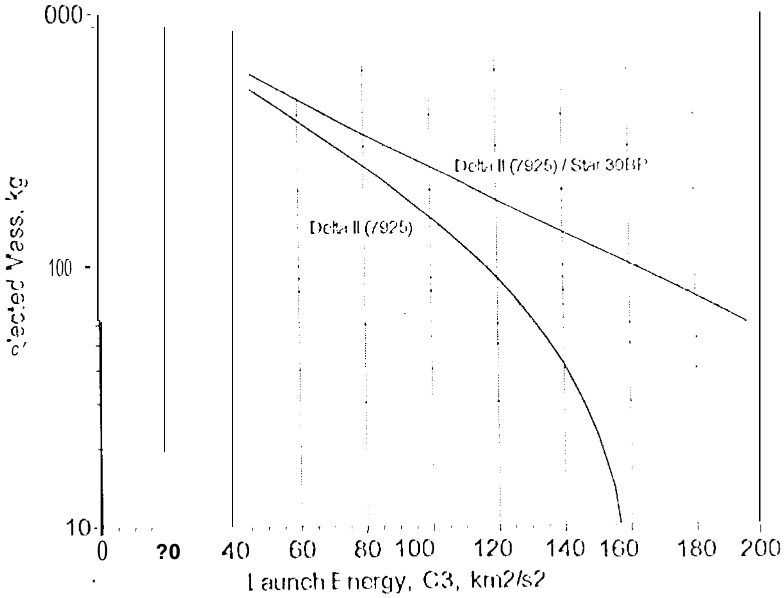


Figure 1: Delta II Launch Vehicle Capability

Figure 2 plots net delivery flyby mass for the Earth to Jupiter launch opportunities from 2000 through 2012. Flight times from Earth to Jupiter in years are shown for each launch opportunity. Figure 3 plots net mass delivered into Jupiter orbit for the same set of launch opportunities as in Figure 2. The example orbit has a Jupiter closest approach radius of 1.05 RJ and a period of 100 days. Two points are plotted for each launch opportunity: the lower point is for direct or two-impulse trajectories, and the upper point is for trajectories which include one deep space maneuver (i.e., broken plane trajectories).

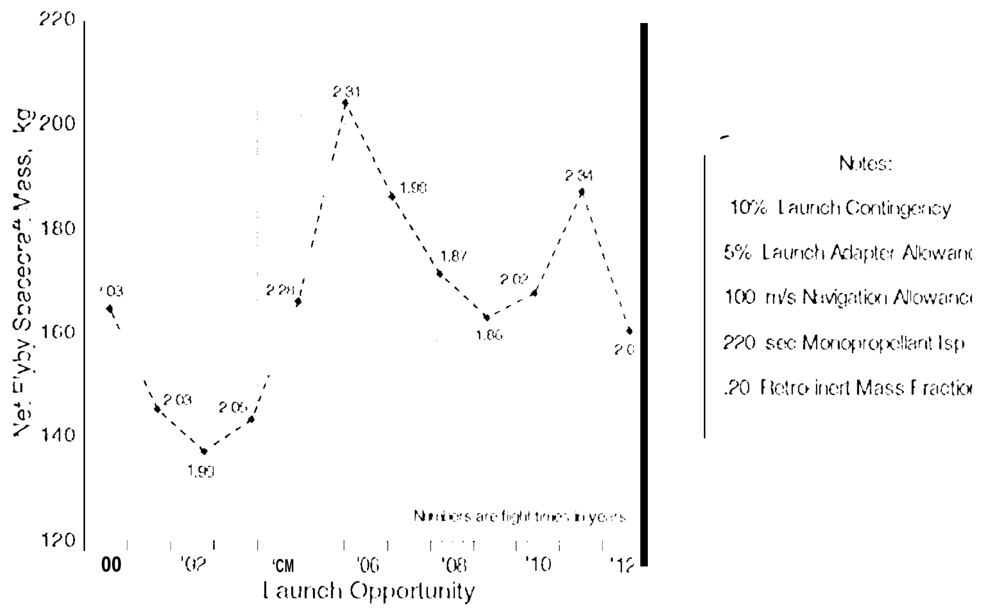


Figure 2: Net Spacecraft Mass at Jupiter Flyby
Delta II (7925) Launch Vehicle
15 Day Launch Period

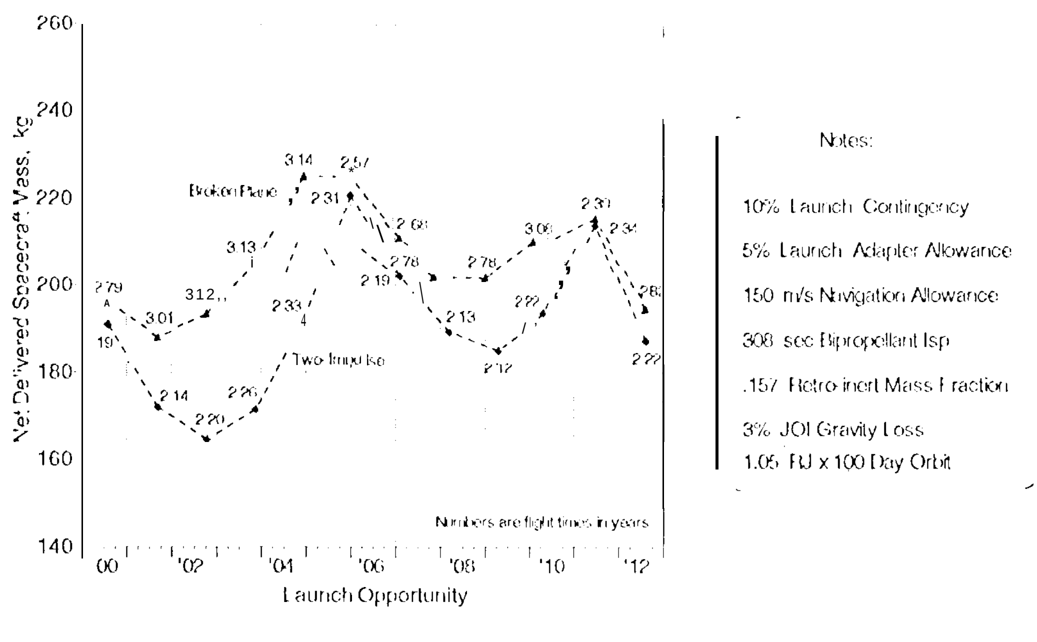


Figure 3: Net Spacecraft Mass in Jupiter Orbit
Delta II (7925)/Star 30BP Launch Vehicle
15 Day Launch Period

MEASURE-JUPITER MISSION CONCEPT DESCRIPTIONS

Two mission concepts were selected by the NASA Outer Planet Science Working Group as scientifically worthwhile, but most importantly to display the typical range of MEASURE-Jupiter mission possibilities with respect to mission cost and complexity. A Galilean satellite flyby was selected for the lower cost example, and a Jupiter polar orbiter selected for the. upper end of the cost range.

Io Skimmer

1 'igure **4 is** a **view** from above the Jupiter system. The 10 Skimmer spacecraft encounters 10 at the lowest relative speed in 10's orbit around Jupiter. Figure 5 is an expanded view of the encounter trajectory. The main objective of the Io Skimmer mission is to sample the 10 **neutral** atmosphere which is thought to lie between 20 and 70 km from **10's surf ace..** This objective is of scientific interest and serves as a challenging test case for the MEASURE- Jupiter missions concept. '1'able 1 lists a strawman Io Skimmer set of science instruments with encounter activities.

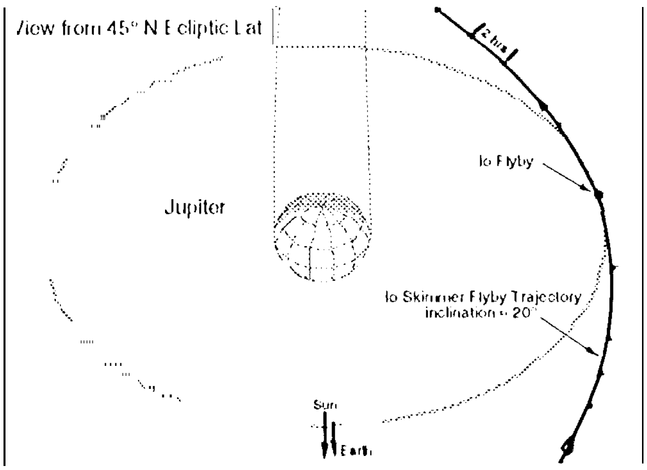


Figure 4: Jupiter Galilean Satellite Flyby Example, Io Skimmer Jupiter-Centered Trajectory

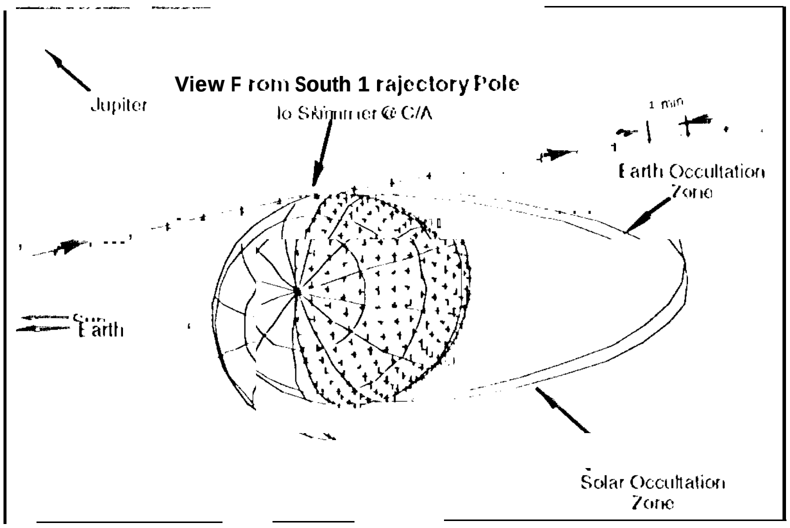


Figure 5: Io Skimmer Strawman Encounter, Io-Centered Trajectory (45-km Flyby Altitude)

Table 1: Strawman Io Skimmer Science Activities

• **Ion and Neutral Mass Spectrometers (5.4 kg / S.4 Watts):**
1011 Mass Spectrometer: Bow Shock Crossing to Closest Approach + 1 day
Neutral Mass Spectrometer: Bow Shock Crossing to Closest Approach + 1 day
if High Energy Capable, Closest Approach ± 7RJ if Energy Limited

• **X-ray Fluorescence Spectrometer (1 .2 kg / 1.2 Watts):**
1 hour of measurements during: Closest Approach ± 1 day and Closest Approach ± 4 hours
Continuous measurements during: Closest Approach ± 30 min

• **Imaging (Vis, UV, IR) * (1 .2 kg / 3.6 Watts):**

Range (kill)	Resolution (m/pixel)	Frames	Comments
20	1	3	Single Frame Coverage
300	15	3	Single Frame Coverage
2000	100	16 frames (4, 2x? mosaics)	Spot Coverage
6000	300	24 frames (?, 4x3 mosaics)	Regional Coverage
?0000	1000	32 frames (8x4 mosaic)	Full Body
60000	3000	6 frames (3x2 mosaic)	Full Body

• **Plasma Energetics Package:** Bow Shock Crossing to Closest Approach + 1 day

* 20-km Io closest approach flyby altitude (worst case for measurements in 20 - 70 km target range)

Io Skimmer requires delivery to a 45-km altitude ± 25-km. A preliminary study[2] indicates such delivery accuracy is possible with radio-only tracking. One tracking pass per week Of Doppler and ranging until 30 days before 10 Closest approach, then one tracking pass J) Cl" day Of Doppler and ranging from 30 days before 10 closest approach to Io closest approach would be required to meet the delivery requirement. The 10 ephemeris selected for this navigation study assumes improvements incorporated from the Galileo orbiter mission. The Io Skimmer spacecraft will carry a camera, and optical navigation would likely be incorporated into the mission requirements depending (m cost *vs.* science measurement trade-Offs,

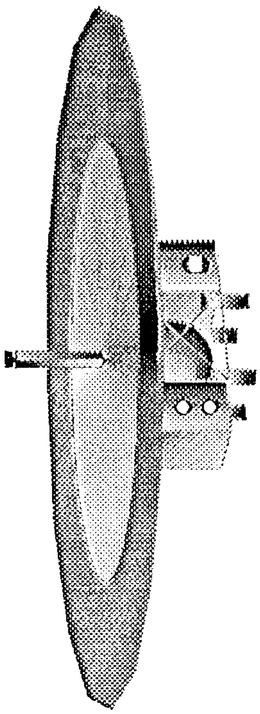
An Io Skimmer spacecraft design that addresses the science objectives outlined in Table 1 is summarized in Figure 6. Three important features of the Io Skimmer spacecraft design are:

- No RTG; use of Low Intensity Low Temperature (LILT) operational silicon solar panel with secondary battery
- Use of a flat high-gain antenna reflector of low mass sharing support structure with the solar panel
- Use of advanced packaging and miniaturization technology

Jupiter Auroral 01)SC1"V(%

Figure 7 is a view of the Jupiter system with both the approach trajectory and orbit of the Jupiter Auroral Observer (JAO) spacecraft. This mission utilizes a Jupiter polar orbit to observe. the. poles of Jupiter, and in particular the auroras at the poles. A true trajectory view of the encounter is shown in Figure 8. Table ? provides the strawman science objectives and science instrument payload with mass and power requirements. Figure 9 is a plot Of a strawman encounter profile as a function of instrument activity, range to Jupiter, and time of Jupiter closest approach - derived from the science objectives in Table 2.

The Jupiter Aurora] Observe.r spacecraft design that addresses the science objectives outlined in Table 2 is summarized in Figure 10. The JAO spacecraft design is similar to the 10 Skimmer with two important exceptions: 1) the JAO spacecraft requires greater propulsion capability so that it can perform maneuvers imparting nearly 1 .0 km/s of impulse to its trajectory during its mission (most of the propellant required will be used in achieving Jupiter orbit insertion); and 2) deployable solar arrays of larger size are required to allow trickle-charging the secondary battery consistent with the JAO 100-day mission sequence cycle. Instead of one encounter with subsequent data playback, the JAO spacecraft could be thought of having an encounter every 100 days with data playback occurring during the subsequent 1 00 days.



PERFORMANCE

Attitude Control	3 axis attitude control system sun sensor and star scanner for attitude determination 0.9 N thrusters for roll and attitude control cold gas thrusters
Telecommunication	all x-band, 3 W solid state power amplifier 1.5 m flat, high gain antenna low gain antenna for off-earth pointing
Spacecraft Data	central processor R3000 2 G bits solid state memory
Power	3.2 m2 Si solar array, - 21 W @ Jupiter LiTiS2 secondary batteries, 125 Whr/kg
Propulsion	monopropellant (N2H4) system, total AV 150 m/s
Thermal Control	passive system of multi-layer insulation, and coatings RHUs for temperature control
Structure	composite bus and truss structure and support elements fuel tank housed within main spacecraft structure

MASS (KG)	
Attitude Control	6.7
Telecommunication	13.2
Spacecraft Data	7.8
Power	21.5
Propulsion	9.4
Thermal	4.0
Structure	20.2
Cabling	5.5
Science	10.0
Subtotal	94 D
30% Contingency	28.5
Dry Spacecraft	123.4
Propellant	7.7
Wet Spacecraft	131.9

POWER [W]	
Attitude Control	7.3
Telecommunication	24.0
Spacecraft Data	8.0
Power	12.4
Propulsion	0.9
Thermal	0.0
Structure	0.0
Cabling	0.0
Science	0.0
Subtotal	52.G
30% Contingency	15.9
Total Spacecraft	68.5

Worst Case: Transmit

Figure 6: Io Skimmer Preliminary Systems Design

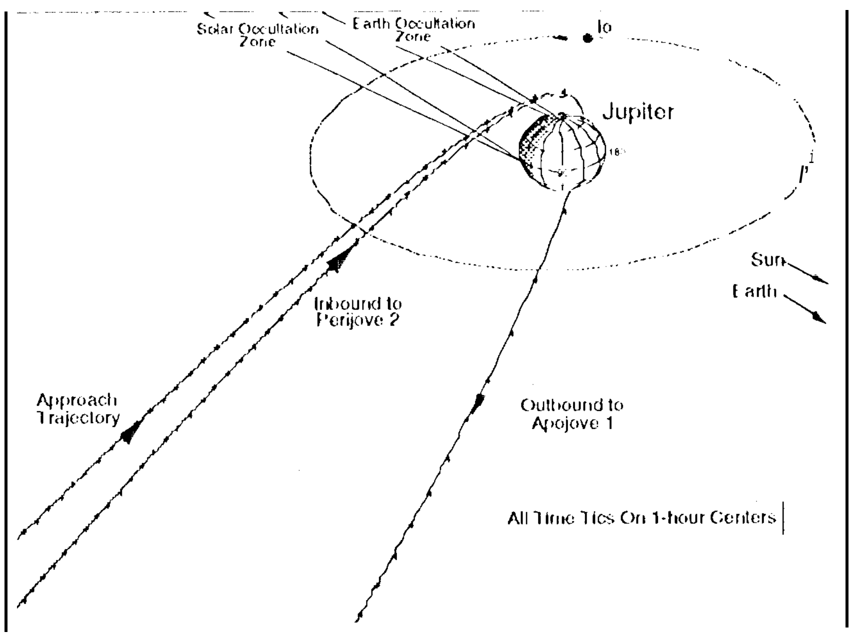


Figure 7: Jupiter Auroral Observer: Overview Of Mission Orbit

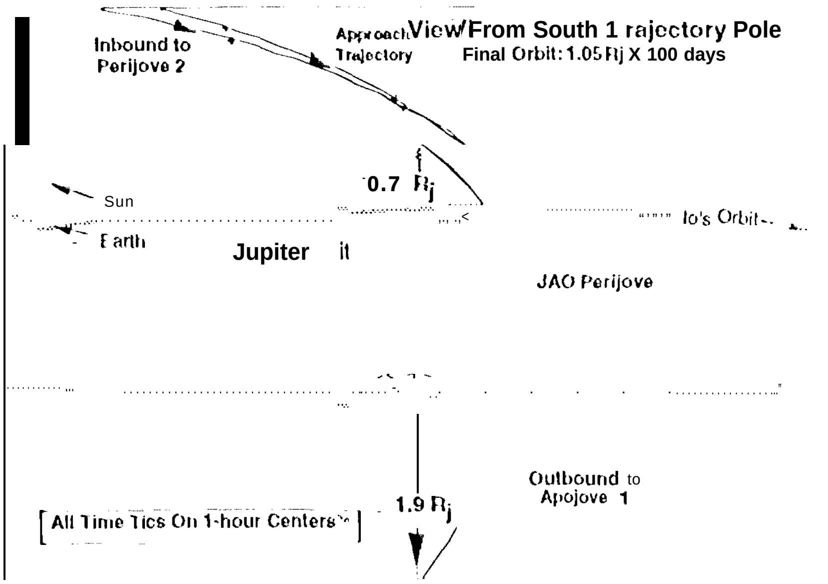


Figure 8: True Trajectory View Of Jupiter Auroral Observer Mission Orbit

Table 2: Jupiter Auroral Observer (JAO) Science Objectives & Strawman Payload

- Science Objectives:
  - Monitor the appearance of Jupiter's polar aurorae al UV and NIR to determine the source region(s) in the magnetosphere and the processes responsible for producing aurorae.
  - Monitor plasma and magnetic fields at high latitudes and relate auroral activity to the observed state of the magnetosphere.
  - Secondary Objectives:
    - Determine the structure of Jupiter's inner magnetic field to infer the nature of currents in the deep interior which produce it
    - Measure the ammonia abundance and temp./press. profile of Jupiter's atmosphere from 0.01 bar to 2 bar at many latitudes (via radio occultations †) and derive information on atmospheric waves
- Strawman Science Payload:

Instrument	Mass (kg)	Power (watts)
UV Imaging	3	2
NIR Imaging	2	2
Spectormeter	2.3*	4.5*
Charged Particles		
Radio/Plasma Wave	?	2
Magnetometer	2	2
Totals	11.3	12.5

* Includes 10% for motor which can be eliminated for a spinning s/c
† Requires USO that is currently not in payload

TECHNOLOGY

The mission and system design approach for MEASURE-Jupiter is simply put:

Really Low Cost - Really Simple - no RTGs

The two example mission/system designs described above validate this approach, given that elements of advanced technology are available. Key elements of technology developed by and for the Pluto Fast Flyby mission[2] will be required by the MEASURE-Jupiter missions:

- High density/low mass electronic packaging
- Advanced/micro spacecraft technology (allowing miniaturization of most subsystems, including attitude control, power, transponder, memory, propulsion, and thermal)

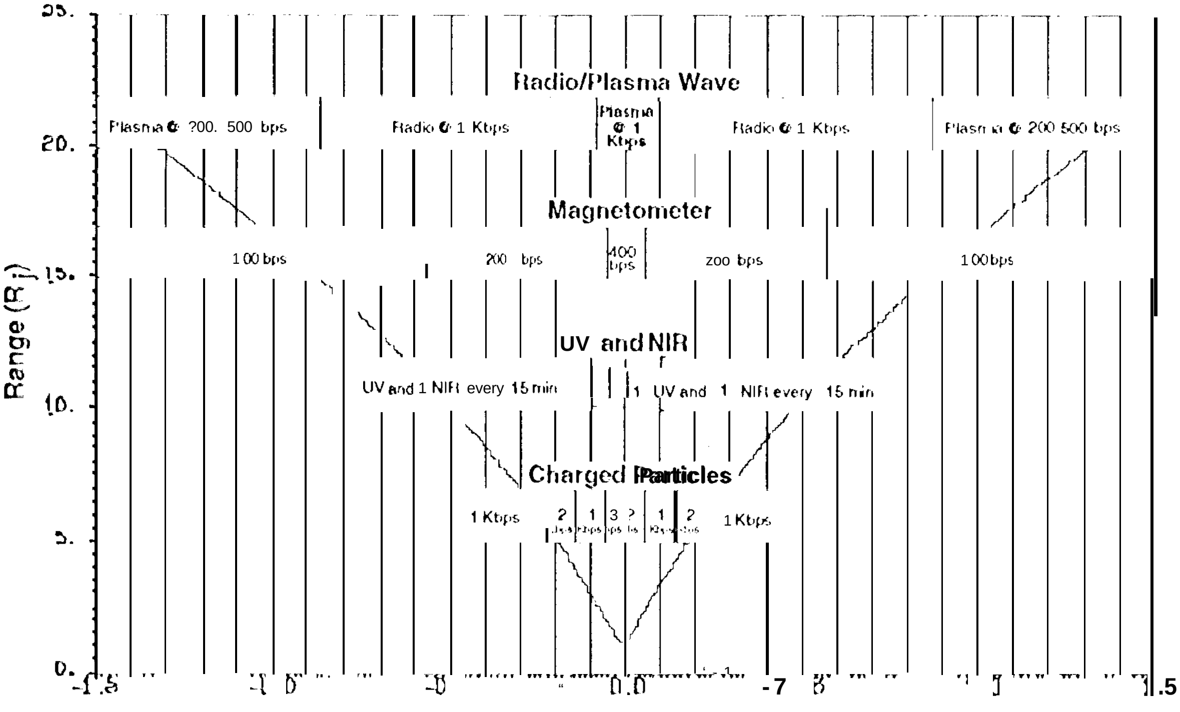
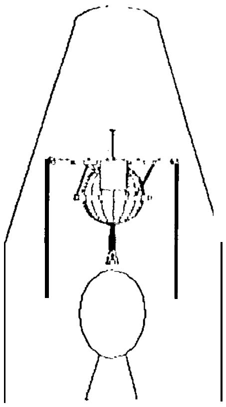
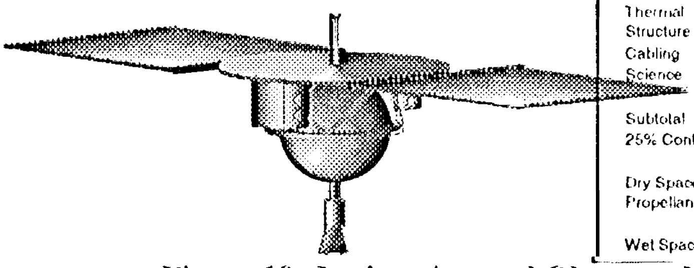


Figure 9: Jupiter Auroral Observer Encounter Profile



PERFORMANCE

Attitude Control	3 axis attitude control system sun sensor and star scanner for attitude determination 0.1 N thrusters for roll and attitude control sun pointed during cruise and on orbit
Telecommunication	all x-band, 3 W solid state power amplifier 1.5 m flat, high gain antenna low gain antenna for off-earth pointing
Spacecraft Data	central processor R3000 2 Gbits solid state memory
Power	2 x 2 75 m2 Si solar array, ~35 W @ Jupiter LIT iS2 secondary batteries, 125 Whr/kg
Propulsion	monopropellant (N2H4) system, total ΔV 972 m/s 445 N ΔV thrusters for JOI and deep space maneuver
Thermal Control	passive system of multi layer insulation and coatings RHUs for temperature control
Structure	composite bus and truss structure and support elements fuel tank housed thin main spacecraft structure



MASS (KG)

Attitude Control	6.7
Telecommunication	13.2
Spacecraft Data	7.8
Power	42.0
Propulsion	27.8
Thermal	4.2
Structure	24.0
Cabling	8.7
Science	10.0
Subtotal	145.6
25% Contingency	36.5
Dry Spacecraft	182.1
Propellant	100.9
Wet Spacecraft	?83.0

POWER (W)

Attitude Control	7.3
Telecommunication	24.0
Spacecraft Data	8.0
Power	1?4
Propulsion	0.8
Thermal	0.0
Structure	0.0
Cabling	0.0
Science	0.0
Subtotal	5?6
30% Contingency	15.9
Total Spacecraft	68.5
Worst Case: Transmit	

Figure 10: Jupiter Auroral Observer Preliminary Systems Design

In addition to the above, other advanced technologies are required for MEASURE-Jupiter:

1) Low Intensity/Low Temperature (LILT) silicon solar array cells
2) High-density, large-cycle secondary battery
3) Low mass flat high gain antenna

Development time required to bring each of these three technologies above to the level required for the MEASURE-Jupiter missions is estimated at between 1 and 3 years with an attendant funding requirement for each of from $1 to $5 million.

JOVIAN SYSTEM ENVIRONMENTAL RISK

Dust in orbit around Jupiter is thought to lie in the equatorial region from 1.7 to 3 Rj [4]. The densest and most hazardous part of this region lies between 1.79 and 1.81 Rj and should be avoided. Other portions of the dust region might be traversed with the addition of a dust shield. Neither of the two MEASURE-Jupiter mission examples described above enter the dust hazard region.

The most intense radiation regions around Jupiter lie in the equatorial region beyond 1.0 Rj altitude[5]. For this reason the Io Skimmer spacecraft radiation exposure would be more severe than that experienced by the Jupiter Auroral Observer spacecraft. The system design for both spacecraft considered the worst case exposure experienced by the Io Skimmer. Design features to meet radiation hazard requirements include: 75 krad design (with 2RDM) utilizing internal and block redundancy to provide resiliency. Options to further increase resiliency include Error Detection and Correction, watchdog timer, and power-off methods (to prevent Single Event Phenomena).

COST ESTIMATES

Both the Io Skimmer and Jupiter Auroral Observer mission concepts were costed to the level of system definition available from the JPL four-month preliminary design effort. Three preliminary estimates were made, two at JPL (one rough top-down and one subsystem by subsystem bottom-up) and one from SAIC[6]. A single flight system cost was averaged for a lower-end Galilean satellite flyby mission and an upper-end polar orbiter mission. Life-cycle costs are shown below in Table 3 in Real Year dollars.

Table 3: MEASURE-Jupiter Mission Cost Estimates
(In Millions Of Real Year Dollars)

Cost Items	Satellite Flyby	Polar Orbiter
• Development:		
Flight System	60	80
Other Development*	45	53
Sub-Total	105	133
30% Reserve	32	40
Total Development	137	173
• Launch Vehicle:		
Delta II (7925)	55	55
Star 30BP (with Integration)	0	10
Total Launch Vehicle	55	65
• Mission Operations & Data Acquisition:		
(Flight Time/Encounter Time)	(2 yrs/0.5 yrs)	(2.5 yrs/1yr)
Post-Launch Cost	15	25
• Total Life-Cycle Cost:	207	263

*Including Project management, mission analysis and engineering, Project science, science instruments, and mission operations system development.

The above figures are rough, but do indicate that MEASURE-Jupiter mission concepts can be designed to lie in the small mission category.

CONCLUSIONS

The MEASURE-Jupiter concept is an exciting low-cost mission approach for exploration of Jupiter in the post-Galileo era. The concept assumes technology heritage from the Pluto Fast Flyby mission and modest advances in three technology areas: 1,11,'1' silicon solar array cells, high (11'.ilsity/l2llgc-cycle secondary batteries, and low mass flat high gain antennas.

The four-month study carried out at JPL under the guidance of NASA's Outer Planet Science Working Group has resulted in the validation of the MEASURE-Jupiter concept. Selection of scientifically rewarding concepts for next-level mission and system definition is scheduled for later in 1994 with analysis of selected concepts proceeding into 1995. Launches as early as 2000 could be possible under various NASA programmatic strategies.

ACKNOWLEDGMENT

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